

## **Layered Organization in the Coastal Ocean: 4-D Assessment of Thin Layer Structure, Dynamics and Impacts**

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### **LONG-TERM GOALS**

Our long-term goal is to understand (1) the properties of densely concentrated, thin layers of planktonic biota that can occur in coastal ocean environments, (2) the interacting physical, chemical, biological and optical processes responsible for establishment, maintenance and breakdown of layers, (3) the impact of thin layers on the dynamics of plankton populations and the performance of optical sensors, and (4) how the above vary between coastal systems that differ in physical size, exposure to physical forcing, and susceptibility to episodic events.

### **OBJECTIVES**

Our objectives for this LOCO project are (1) to understand the physical, biological, optical, chemical and acoustical properties of vertically thin horizontal layers of biota and biogenic particles in coastal oceans, and the processes responsible for the formation, maintenance and dissipation of layers; (2) to understand the spatial coherence and spatial properties of thin layers in the coastal ocean (especially in terms of optical properties), as well as the temporal durability of layers, where they occur; and (3) to use the information gleaned in the first two objectives along with data from our studies in other coastal systems to test and refine our models of thin layer dynamics (Donaghay and Osborn, 1997) and thus continue to develop the ability to predict layer formation and presence in the coastal ocean. Our primary objectives during the past 12 months of this grant have been to (1) process the raw data from the 2005 and 2006 LOCO field experiments into master data files that include all measured and derived parameters, and (2) begin to use the data to address our overall scientific objectives. Our secondary objective was to continue to publish the results of our previous work on thin layers.

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## APPROACH

Our approach during the 2005 and 2006 LOCO process study combined time series data from an array of our Ocean Response Coastal Analysis System (ORCAS) autonomous bottom-up profilers with spatial data collected over a broader area using our ship-deployed, high-resolution profiler. These efforts were done in close collaboration with LOCO projects led by Holliday, Hanson, Rines, Goodman, and McManus. Our efforts are discussed below along with collaborations in collecting and analyzing the data.

The first major component of our effort involved using an array of autonomous profilers to simultaneously collected temporal data on the spatial variations in vertical fine-scale physical, chemical, optical, and acoustical structure. We deployed two of our ORCAS bottom-up profilers 100 m apart in the cluster located at K1 and a third profiler at station K2 located 1 km further offshore along the cross-shelf K line. This design allowed us to sample simultaneously at two different spatial scales. The profilers collected centimeter-resolution profiles at least once an hour of temperature, salinity, depth, oxygen, spectral absorption, spectral attenuation, spectral scattering, backscatter at 532 nm, chlorophyll a fluorescence, and CDOM fluorescence. Our ORCAS profilers at K1 South and K2 had a Nortek ADV (Acoustic Doppler Velocity meter) for simultaneously measuring centimeter- scale currents and turbulence. Our ORCAS profiler at K1 North had the same suite of sensors as the other profilers except that had additional sensors for nutrients (a SubChem Systems autonomous nutrient analyzer provided by Hanson) and light (Satlantic OCR-4 downwelling light sensor). In addition, the multi-spectral WET Labs ac-9 was replaced on this profiler with a WET Labs ac-s hyper-spectral absorption and attenuation and meter. Other time series sensors at each of these locations included a TAPS multi-frequency acoustics zooplankton profiler deployed by Holliday, an ADCP for measuring currents and current shear once a minute with 25-50 cm resolution (deployed by Holliday or McManus) and a thermister string for measuring internal waves (deployed by Holliday or McManus). Data from our array of profilers was radioed to shore at the end of each profile. Near-real time preliminary analysis of this data was used to quantify temporal changes in physical, chemical and optical structure and look for the occurrence and extent of thin optical layers. These results were communicated to the other PIs by e-mail and used to guide ship-based sampling efforts. Analyses of these data during this next year will be used to (1) detect the presence, intensity, thickness, temporal persistence, and spatial coherence of thin optical and acoustical layers, (2) quantify their optical and acoustical characteristics, and (3) quantify their association with physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics.

The second major component of our effort involved using the R.V. Shana Rae to periodically collect ship-deployed high-resolution profiles needed to (1) validate the measurements made by the autonomous optical profilers, (2) characterize the larger scale spatial variability in the fine-scale structure detected by the array, and (3) further characterize the inherent optical properties of thin layers detected by the array. Our high-resolution profiler had the same sensor suite as the bottom-up IOP profilers plus a PAR light sensor, a second WET Labs ac-9 with a 0.2 micron pre-filter for measuring spectral absorption by dissolved substances, a pair of WET Labs ac-s high-spectral resolution absorption and attenuation meters (one without and 1 with a 4 micron pre-filter to measure absorption, attenuation and scattering by small particles for spectral characterization of particulate and dissolved material), and a SubChem analyzer (provided by Hanson - see his report) for measuring fine-scale nutrient structure. We plan to combine these data with data from the array

to define (1) the spatial variability along-shore and cross-shore in layer thickness, intensity, optical characteristics, and biological composition, and (2) the association of these changes with changes in the physical, chemical and biological structures and processes that have been hypothesized to control thin layer dynamics. We also plan to eventually combine these data with similar physical and optical data that Cowles collected in deeper water to determine the along-shore and cross-shore dimensions of any thin layers that extend outside the local region that we plan to sample.

The third component of our effort involved using the R.V. Shana Rae to periodically collect plankton samples from inside and outside thin layers. Real-time data from our high-resolution profiler was used to guide the collection of plankton samples from inside and outside thin optical layers using a rosette bottle sampler. Rines (see her LOCO report) is using these samples to identify the biological composition of the plankton. In addition, we collaborated with Holliday in using real-time data from his TAPS array to guide collection of net samples needed to identify the composition of zooplankton present and collect photographic images of zooplankton needed for inversion of the acoustic data on zooplankton distributions (as planned by Holliday). We also periodically towed our newly acquired Laser Optical Plankton Counter (LOPC) along the K line to collect optical data on the abundance, size and shape of the zooplankton that were being measured by Holliday's TAPS at K1 and K2 and by the multi-frequency acoustic profilers deployed from the Shana Rea by Benoit-Bird.

## **WORK COMPLETED**

**Publication of papers on thin layers.** We have published seven papers this year. The first paper (Churnside and Donaghay, 2009) examines the frequency of occurrence, spatial extent, and characteristics of thin optical backscattering layers in coastal and open ocean areas of the North Pacific and North Atlantic using 80,000 kilometers of high vertical and horizontal resolution optical backscatter data collected by James Churnside (NOAA) during tests of an airborne LIDAR that he developed to survey epipelagic fish. This paper was published in the ICES Journal of Marine Science. The second paper (Holliday, et al, 2009) examines the interactions between thin layers formed by migrating phytoplankton and zooplankton. This paper was published in the ICES Journal of Marine Science. The third paper (Sullivan, et al, 2009a) examines the patterns of occurrence and characteristics of thin layers measured by the ORCAS profilers during 2002, 2005 and 2006. This paper is published in the LOCO special issue of Continental Shelf Research. The fourth paper (Holliday, et al. 2009) examines the patterns of occurrence and characteristics of thin acoustic layers measured by Holliday's TAPS and their relationship to the thin optical layers measured by our ORCAS profilers in Monterey Bay during 2002, 2005 and 2006. This paper is published in the LOCO special issue of Continental Shelf Research. The fifth paper (Rines, et al, 2009) examines the relationship between thin optical layers and the vertical structure of large phytoplankton. This paper is published in the LOCO special issue of Continental Shelf Research. The sixth paper (Ryan, et al, 2009) applies the algorithms we developed for detecting and characterizing thin layers to the MBARI AUV survey data to assess the temporal and spatial extent of thin layers observed in Monterey Bay in 2005. This paper is published in the LOCO special issue of Continental Shelf Research. The seventh paper is an introduction to the special issue on the LOCO experiment (Sullivan et al, 2009b).

**Editing the special issue of Continental Shelf Research.** Sullivan and Donaghay co-edited (with Margaret McManus) a special issue dedicated to the ONR LOCO experiment. Sullivan took the

lead in this effort and served as the managing guest editor. The papers have all been reviewed and the accepted for publication this fall.

**Presentation of LOCO results at international meetings and workshops.** Donaghay presented an invited plenary talk at the 2008 Ocean Optics Conference entitled "Evolution of Profiling Systems for Understanding the Characteristics, Distributions, Dynamics and Impacts of Thin Plankton Layers in Stratified Waters".

**Preparation of additional papers on the LOCO experiments.** We have completed two additional manuscripts on the LOCO experiment. The first paper (McFarland, et al) examines the relationship between thin optical layers and the vertical structure of very small phytoplankton (picophytoplankton). This paper is titled "Distributions of photosynthetic picoplankton relative to thin optical layers in Monterey Bay, CA" with McFarland, Rines, and Donaghay as authors. We plan to submit this paper to Limnology and Oceanography. The second paper (Graff et al) examines the relationship between thin layers and bacterial colonization of phytoplankton in coastal waters. This paper is titled "Bacterial colonization of phytoplankton in the pelagic marine environment" with Graff, Rines and Donaghay as authors. We plan to submit this paper to Marine Ecology Progress Series.

## **RESULTS**

The results of our research have been described in previous yearly reports. These results are summarized in the above publications.

## **IMPACT/APPLICATION**

One of the central assumptions in biological oceanography has been that small scale mixing processes in the upper ocean are sufficiently strong and equal in all directions that sub-meter scale biological, chemical and optical structures will be rapidly dispersed and thus can be ignored in both sampling and modeling upper ocean dynamics. Results from our measurements of fine-scale structure in East Sound (WA), Monterey Bay (CA), the Gulf of Mexico, and off the west coast of Ireland clearly indicate that this assumption is frequently incorrect. These measurements also indicate that the accurate assessment of occurrence, intensity, spatial extent, and temporal persistence of thin optical layers requires centimeter-scale sampling. Our field results and theoretical analyses indicate that biological-physical, biological-chemical and biological-biological interactions occurring at these scales may control not only the development of blooms of toxic and/or bioluminescent phytoplankton, but also the extent to which zooplankton are able to exploit phytoplankton production. Equally importantly, collaborative analysis of the data with experts in optics indicates that fine-scale biological layers can become sufficiently intense at times to alter the performance of optical and acoustical sensors in coastal waters. These analyses also suggest that our bottom-up profiling systems have considerable potential for increasing our understanding biological dynamics and improving our interpretation of optical and acoustic data collected by other platforms.

## **TRANSITIONS**

Our ORCAS profiler technology has now been successfully transitioned to three different groups through our collaborative efforts to commercialize the technology with WET Labs. First, Dr. Benjamin Cray (NUWC) has purchased and successfully deployed a modified Mini-AMP version of the profiler equipped with a CTD, ADV and an array of advanced acoustic sensors. Second, we have collaborated with WET Labs and Jack Barth (OSU) in developing an NSF funded version of the profiler suitable for extended deployment on the Oregon shelf. Third, NOAA has purchased and successfully deployed a WET Labs Mini-AMP profiler for use in one of its programs in Chesapeake Bay.

## **RELATED PROJECTS**

This LOCO project has been developed in close collaboration with Van Holliday (URI/BAE Systems) and a core group of independent investigators that include Jan Rines (URI), Louis Goodman (SMAST), Edward Levine (NUWC), Alfred Hanson (SubChem Systems), Margaret McManus (UH), John Ryan (MBARI) and Timothy Cowles (OSU). We have collaborated with these investigators for several years. This year we have worked closely with Goodman in the analysis of the ADV and other physical data collected during the LOCO experiments. We have shared data sets with Goodman and Sullivan has worked closely with him in designing our approach to analyzing the turbulence data from the ADV. We have also work closely with Hanson in analyzing the nutrient data collected by our autonomous ORCAS IOPC profiler and ship-deployed Hi-Res profiler.

## **PUBLICATIONS**

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3. Sullivan, J.M., Donaghay, P.L., Rines, J.E.B., 2009a. "Coastal thin layer dynamics: consequences to biology and optics". Continental Shelf Research, LOCO Special Issue.
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5. Rines J, , M.N. McFarland, P.L. Donaghay, and J.M. Sullivan, 2009. "Thin layers and species-specific characterization of the phytoplankton community in Monterey Bay, California USA." Continental Shelf Research. LOCO Special Issue.

6. Ryan, J.P., McManus, M. A., and Sullivan, J.M., 2009. Physical, chemical and biological forcing of phytoplankton thin-layer variability in Monterey Bay, California. *Continental Shelf Research, LOCO Special Issue*.

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